Band Structure Engineering for Ultra-low Threshold Laser Diodes

Progress Report for Contract #N00014-88-C-0611

I. Ury and Kam Y. Lau[1]

Ortel Corporation

2015 W. Chestnut St., Alhambra, CA91803

It has been proposed that strained layer superlattice be used to reduce the effective mass of holes, thereby reducing the transparency electron density and subsequently the lasing threshold. In conventional bulk materials, the degeneracy of heavy and light hole bands at zone center means domination of the heavy hold band in hole occupation. It was known that by applying strain to the crystal, the degeneracy can be broken such that under a biaxial compressive stress, the light hole band is lifted above the heavy hole band in the k-vector directions parellel to the applied strain. Since the heavy hole is five times heavier than the light hole, the resultant effective hole mass can be reduced by a factor of 5. The strain can be built in by growing lattice-mismatched InGaAs on GaAs substrate. Such lattice-mismatched epitaxial layers cannot be arbitrarily thick for it to be defect free, the maximum thickness being only about 100Å. Thus all strained layer structures are by default quantum well structures, and it appears that the same argument above, that of lifting the light hole band above the

Indium compounds, Gallium Arsenide, ([illegible])

1 Permanent Address : Columbia University, Dept. of Electrical Engineering, New York, N.Y.10027.

heavy hole band by strain, can be applied to predict that strained quantum wells have an effective hole mass five time lower than that of unstrained quantum wells.

It is clear from the discussions in the above that a low density of states results in a low transparancy electron density. What is not so clear is how a low density of states results in a higher differential gain, afterall, a low density of states means that at any particular photon transition energy there are fewer states available and hence the gain should be reduced. It will be shown that this is true only at very high carrier densities, and if one designs a laser which does not require a very high gain for lasing, the enhancement in differential gain is substantial. Strained layer lasers should therefore exhibit a higher modulation speed compared to a regular quantum well laser, provided that the laser parameters are properly designed.

The optical gain is given by

$$g(E) = \xi \rho_r (f_c + f_v - 1)$$

where

$$\xi = \frac{\bar{h} \pi q^2 |M|^2}{\epsilon_0 m_0^2 c n_r E}$$

is a material dependent parameter, $E = \bar{h}\omega - E_g$ is the reduced photon energy, n_r is the index of refraction, and $f_{c,v}$ are the Fermi factors

$$f_{c,v} = \frac{1}{\exp(E - E_{fc,fv})/kT + 1}$$

The energies are measured positive into the conduction band from the (quantized) conduction band edge and positive into the valence from the valence band edge. For a 2D quantum well whose density of states is independent of energy, the reduced density of states ρ_r is the harmonic mean of the electron and hole density of states:

$$\frac{1}{\rho_r} = \frac{1}{\rho_c} + \frac{1}{\rho_v} = L_z \bar{h}^2 \pi \left(\frac{1}{m_c} + \frac{1}{m_v} \right)$$

For transition obeying the k-selection rule, the electron and hole energies are related by

$$E_{c,v} = E \frac{m_r}{m_{c,v}} = \frac{\rho_r}{\rho_{c,v}}$$

The quasi-Fermi levels are related to the electron and hole densities by

$$n, p = \int_0^\infty \rho_{c,v}(E_{c,v}) f_{c,v}(E_{c,v}, E_{fc,fv}) dE_{c,v}$$

which can be evaluated for a constant density of state (as in the case of strained layer quantum well considering the first quantized state only) to give

$$n, p = \rho_{c,v}\{E_{fc,fv} + kT \ln(1 + \exp(-E_{fc,fv}/kT))\}$$

Let the hole density of states be D times that of the electron density of states. Then, equating n and p under the charge neutrality condition yields the following relation between E_{fc} and E_{fv}:

$$e^{-\frac{E_{fv}}{kT}} + 1 = \left(e^{-\frac{E_{fc}}{kT}} + 1 \right)^D$$

The gain spectrum of the strained quantum well is thus

$$g(E) = \xi \rho_r \left(\frac{1}{1 + e^{(E_c - E_{fc})/kT}} + \frac{1}{1 + e^{(E_v - E_{fv})/kT}} - 1 \right)$$

It can be easily seen that the maximum of this gain curve occurs at E=0, i.e., $E_c = E_v = 0$. Thus the maximum gain g_m is given by

$$g_m = \xi\rho_r\left(\frac{1}{1+e^{-E_{fc}/kT}} + \frac{1}{1+e^{-E_{fv}/kT}} - 1\right)$$

which can be converted to a relation that contains only a single variable, the electron quasi Fermi level:

$$g_m = \xi\rho_r\left(\frac{1}{(e^{-E_{fc}/kT}+1)^D} + \frac{1}{e^{-E_{fc}/kT}+1} - 1\right)$$

Notice that this equation satisfies the Bernard-Duraffourg transparency condition : when $E_{fc} + E_{fv} = 0, -E_{fc} = E_{fv}$ and g_m=0. It has been shown that the carrier lifetime in a quantum well structure is almost inversely proportional to the carrier density n, with the experimentally obtain dependence being $\tau = (2.5x10^9 s-cm^{-3})/n$, from which the injection carrier density can be found for a given n. Using the above equations one can plot the maximum gain versus the injected current density, for various values of D. This is shown in Fig. 1. The current density where g_m crosses zero is the transparency level, and decreases with decreasing D as expected. The maximum achievable gain is also reduced for small D, but this won't be felt until one reaches injection current densities of approximately 2.5kA/cm^2 or higher.

One is interested in the differential gain, dg_m/dn. A closed form solution can be obtained for strained layer quantum well by using :

$$\frac{dg_m}{dn} = \frac{dg_m}{dE_{fc}} \cdot \frac{dE_{fc}}{dn}$$

where

$$\frac{dg_m}{dE_{fc}} = \frac{\xi \rho_r e^{E_{fc}/kT}}{kT} \left(\frac{D}{(e^{E_{fc}/kT})^{D+1}} + \frac{1}{(e^{E_{fc}/kT}+1)^2} \right)$$

and

$$\frac{dn}{dE_{fc}} = \frac{\rho_c}{kT} \left(1 - \frac{1}{e^{E_{fc}/kT}+1} \right)$$

so that

$$\frac{dg_m}{dn} = \frac{\xi}{\rho_c + \rho_v} \left(\frac{\rho_c}{(e^{E_{fc}/kT}+1)^D} + \frac{\rho_v}{e^{E_{fc}/kT}+1} \right)$$

The relaxation oscillation frequency of the laser is given by

$$f_r = \frac{1}{2\pi} \sqrt{\frac{c}{n_r} \frac{P_0}{\tau_p} g'}$$

where we denote dg_m/dn by g', and c is the velocity of light. The photon lifetime is related to the peak gain by

$$\frac{1}{\tau_p} = \Gamma \frac{c}{n_r} g_m$$

and hence the relaxation oscillation frequency is given by

$$f_r = \frac{1}{2\pi} \frac{c}{n_r} \sqrt{\Gamma g_m g' P_0}$$

The important quantity is thus the product $g_m g'$. One can plot f_r against g_m for different values of D, at the same photon density P_0. This is shown in Fig. 2 for constant ρ_c. One striking feature of the plot is that the relaxation oscillation frequency of a regular quantum well laser (D=7) is quite independent of g_m, while that of a strained layer (D=2 or 1) shows a clear maximum. Thus by fitting actual modulation data to theory, one can actually derive the value D, the ratio of the hole to electron density of states, and hence the amount of strain in the quantum well. The plot also shows that the optimum value of D is actually around 2, at which point the relaxation oscillation frequency can be enhanced by a factor of approximately 1.5 by applying strain. Notice also that, in practical cases of InGaAs over GaAs strain structures, the bandgap is lowered and hence lasing wavelength is increased by 20% over GaAs, and therefore if one were to compare the modulation speed at the same optical power, the enhancement is even higher.

Work is now in progress to fabricate InGaAs strained quantum wells on GaAs substrate. Since such quantum wells are grown at substrate temperatures of around 600C, at the present moment it does not seem possible to perform regrowth on the wafer by liquid phase epitaxy (at a minimum temperature of 700C) - a step for fabricating buried heterostructure lasers. We therefore plan to fabricate stripe geometry or ridge waveguide lasers for the strain quantum well, and to measure the relaxation oscillation frequency of the laser. These data will then be fitted to the theoretical calculations above to determine the value of reduction of the effective hole mass in these samples.

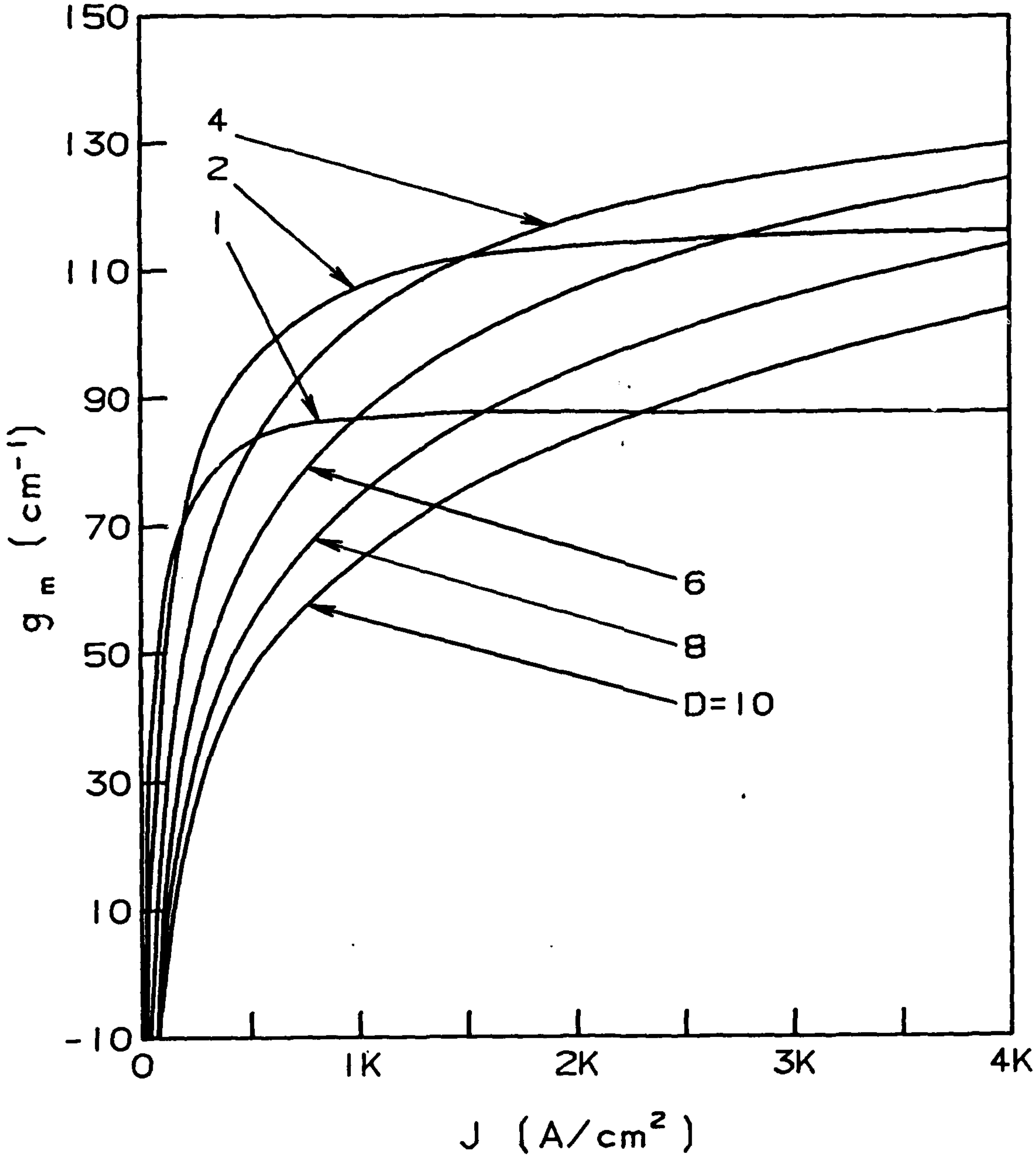

FIGURE 1. MODAL GAIN vs. INJECTION CURRENT DENSITY

KL901258

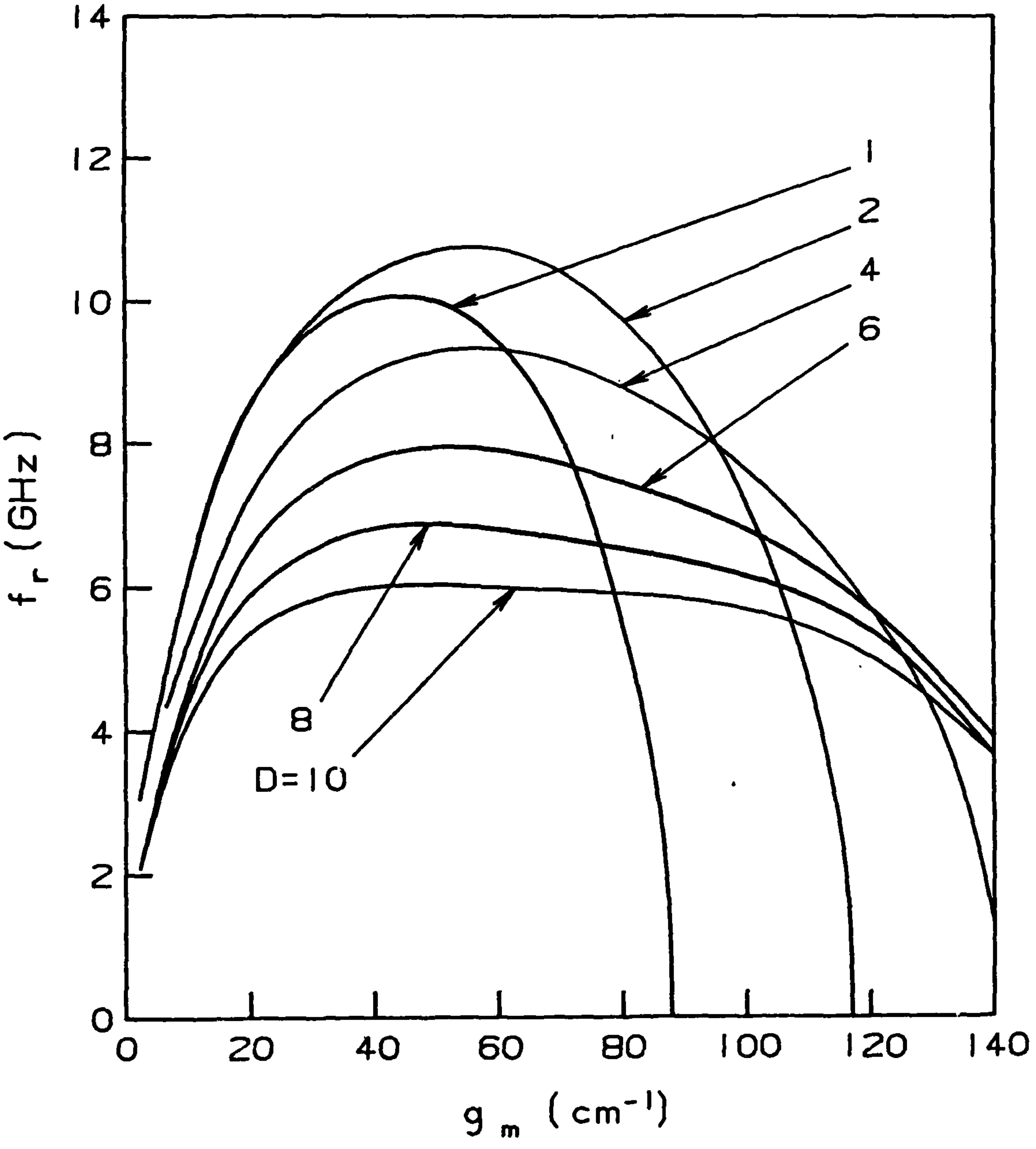

FIGURE 2. RELAXATION OSCILLATION FREQUENCY
vs. MODAL GAIN

KL90125A